1987

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Original Publication Citation

Blanton, J., Tenore, K., Castillejo, F., Atkinson, L., Schwing, F., & Lavin, A. (1987). The relationship of upwelling to mussel production in the rias on the western coast of Spain. *Journal of Marine Research, 45*(2), 497-511. doi: 10.1357/002224087788401115

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Journal of Marine Research, 45, 497–511, 1987

The relationship of upwelling to mussel production in the rias on the western coast of Spain

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ABSTRACT

We have calculated an upwelling index for each month over a 17-year period (1969–1985) for a point off the western coast of Spain. We interpret April through September values of the index to indicate the flux of nitrate-rich water into the Spanish Rias. The index representing the 6-month upwelling series has been correlated with an index representing the conditions of mussels grown during that season on rafts in Ria de Arosa. Two seasons represent extreme upwelling conditions over the 17-year sampling period: 1977 when the upwelling index was the highest, and 1983 when it was the lowest. A comparison of the condition of mussels during these years showed that meat content was double in 1977.

We suggest, by this study, that long range forecasts of synoptic scale weather patterns could be used to predict the potential nutritional value of mussels harvested in the rias of Spain.

1. Introduction

The Rias Bajas on the northwest coast of Spain (Fig. 1) have one of the highest known protein yields of the edible mussel *Mytilus edulis*. This production is carried out on 20 m x 20 m rafts with an average of 600 hanging ropes on which the mussels grow. There are over 2,000 rafts in the Ria de Arosa, the largest of the Rias Bajas. Ria de Arosa annually produces over 100,000 metric tons total wet weight over a total area of 230 km^2 (Tenore *et al.*, 1982). The high production is supported, in great part, from nutrient inputs from the upwelling of nutrient-rich North Atlantic central water along the coast that subsequently is advected into the rias. For further information on the raft culture see Tenore *et al.*, 1982.

Upwelling occurs between the months of April and October (Blanton *et al.*, 1984) when the average winds along the coast exert a southward surface stress causing an Ekman transport offshore. The displaced surface water is replaced by the colder, nutrient-rich deeper water. During the "upwelling" season, the winds actually cycle

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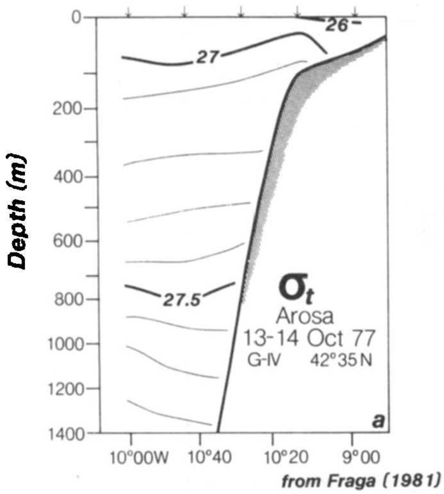
Figure 1. Location map. The dot on the inset map west of Spain is at 43N, 11W, the point where upwelling indices were calculated.

between episodes favoring upwelling and downwelling. These cycles are governed by the synoptic weather patterns which change every 5 to 10 days. Thus upwelling occurs on two basic time scales.

This paper discusses the link between seasonally varying coastal upwelling, nutrient supply to the rias, and the atmospheric system that governs them. An upwelling index, which is related to wind stress, illustrates variations, over time, in the upwelling process (Bakun, 1973). The upwelling index indicates periods during which upwelling theoretically occurs and thus should be related to the influx of nutrient-rich water to the rias. Finally, we examine interannual variations in the strength of upwelling along the coast to determine its relationship to good and bad years for mussel production. The strength and length of upwelling seasons depends, to a large extent, on the position and strength



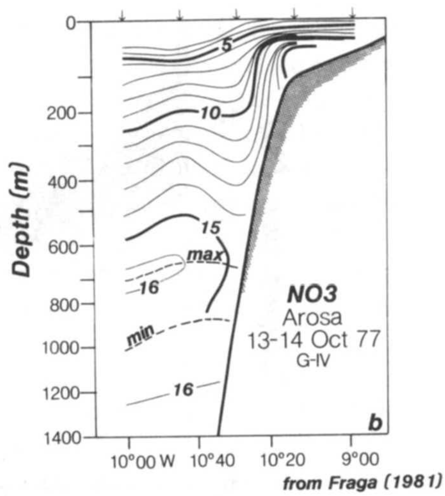


Figure 2. Vertical section off Arosa, 13–14 Oct 1977. (a) σt; (b) nitrate.

of the Azores High pressure cell. This will govern the overall wind field along the western coast of Spain. We will use a mussel condition parameter based on percent solids (meat content) to provide an index of the overall health of the mussel population in a given year. If the position and strength of the Azores High can be successfully predicted, we hypothesize that upwelling along the coast, influx of nutrients into the rias, and hence, the condition of mussels in the rias can also be predicted.

2. The upwelling regime

The western coast of Spain (Galicia) is in an eastern boundary current region of the Atlantic and is influenced by upwelling favorable winds. A vertical section across the continental shelf (Fig. 1) shows that isopycnals several hundred kilometers off the coast and at depths less than 800 m are uplifted approximately 50 m as the edge of the shelf is approached (Fig. 2a). The uplifted water is cold and nutrient-rich (Fig. 2b) thus introducing nutrients to the continental shelf environment when upwelling occurs. A small amount of upwelling can lower temperature by 1–2°C and significantly increase the concentration of nitrate (Fig. 3) in the surface waters. High nitrate values are clearly associated with cold water.

Upwelling occurs frequently off Galicia from April through September (Blanton *et al.*, 1984) due to winds blowing southward along the coast. The upwelling season in a given year can be depicted by graphing daily values of an index representing the onshore or offshore transport of surface water. The index (Bakun, 1973) is equivalent to the Ekman transport derived from surface winds. As pointed out by Wooster *et al.* (1976), "To the extent that this transport is replaced by water from deeper layers,

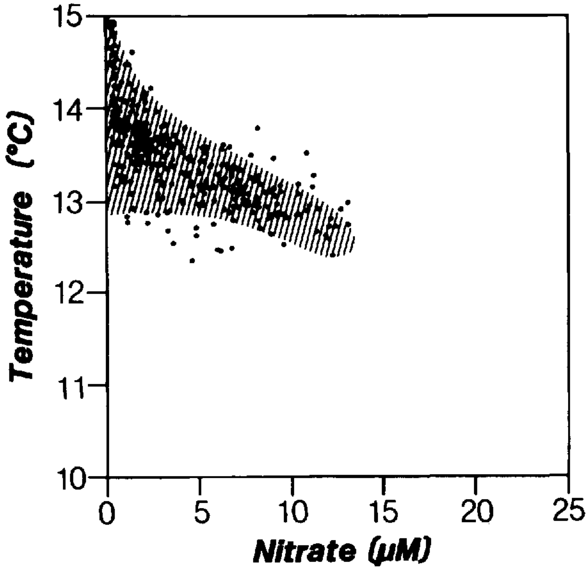


Figure 3. Typical temperature versus nitrate, relationship for ocean water off Galicia. Scatter is caused by nonconservative processes such as nutrient uptake by phytoplankton.

vertical advection is directly related to wind stress." Thus, the upwelling indices used here are equivalent to Ekman transport as calculated by

$$V_e = (1/f)(\tau \times \kappa)$$

where V_e is the transport vector, τ is wind stress vector at the sea surface, f is the Coriolis parameter, and κ is a vertical unit vector. We have rotated the components of V_e so that the offshore component yields the offshore volume transport per meter of shoreline, a volume which we assume is replaced by vertical advection.

We have calculated daily values of V_e (hereafter called upwelling index) for a 17-year period based on geostrophic winds calculated from the sea-surface pressure field for a piont about 150 km west of Cabo Finisterre centered on 43N, 11W (Fig. 1). Geostrophic wind velocity was corrected for surface friction by multiplying speed by 0.7 and rotating direction 15 degrees cyclonically (Haltiner and Martin, 1957). The corrected geostrophic wind was converted to stress, τ, by

$$T = \rho_a C_D |V| V$$

where ρ_a = air density, C_D = drag coefficient = 1.2×10^{-3}, V = the corrected geostrophic wind vector, and vertical bars denote the absolute magnitude.

All available evidence suggests that upwelling and downwelling cycles in the adjacent Atlantic Ocean can transport large volumes of oceanic water into the estuaries of Galicia. A two-layer, linear, hydrodynamical model (Klinck *et al.*, 1981) demonstrated that southward/northward geostrophic currents in the ocean, which are associated with upwelling/downwelling events, controlled sea surface and pycnocline displacements at the mouths of fjord-like estuaries. Because of the resulting pressure gradients set up along the axes of estuaries, the upwelling events drive large volumes of oceanic water into the estuaries below the pycnocline. This process occurs because, during upwelling, surface water in estuaries flows seaward in response to lowered sea level offshore of the mouth. In the case of estuaries off Spain, the surface water is replaced by cold, nutrient-rich oceanic water that flows inward below the pycnocline. Thus the flow of nutrients into these estuaries is in direct response to upwelling events driven by alongshore wind stress.

Fluctuations of sea level in the estuary, as driven by fluctuations in the northward component of wind stress, provide the mechanism to transport nutrient-rich water into the rias. We have calculated the power spectra of a 4-year record (1977–1980) of wind stress and sea level at La Coruna (Fig. 4). The highest variance in both wind stress and sea level occurs near the annual frequency. The next highest variance occurs between 40 and 70 days, which we interpret as a seasonal fluctuation. There are also common spectral peaks at the 16–20 day time scale that are probably related to passing storms and weather fronts. The high correlation between coastal sea level and wind stress in a 16–20 day time scale is verified in a plot of bi-weekly averages of the upwelling index (based on northward wind stress) and sea level in Ria de Vigo (Fig. 5).

Data obtained at the mouth of Ria de Vigo (Fraga and Mourino, 1978) together with our data on upwelling indices and sea level in the ria, link these processes (Fig. 5). Bi-weekly averages of upwelling indices show that a distinct upwelling season began in April, 1977, and lasted until September. During the remainder of the months, downwelling occurred. The 1977 cycle in upwelling indices is reflected in bi-weekly averages of sea level. During downwelling, sea level was relatively high above a 4-year (1977–1980) mean of zero due to southerly winds which drive water toward the coast. During the upwelling season, when winds drive water away from the coast, sea level was below the 4-year mean. Temperature and nitrate data at the mouth of Ria de Vigo correlated well with the upwelling season. At depths below 30 m, ocean temperatures were less than 12°C and nitrate values were higher than 5 μm. Thus, the high nitrate water at the mouth of the ria is a direct consequence of the alongshore component of circulation associated with wind stress off the coast of Spain.

3. Interannual variations in upwelling indices

We have derived monthly mean cycles in upwelling indices based on monthly averages of the sea-surface atmospheric pressure field (U.S. Navy, 1955). While averaging over 20 years has diminished the magnitude of the gradients, a clear annual cycle of upwelling and downwelling is apparent (Fig. 6). Strongest upwelling occurs in April followed by June and July. Strongest downwelling occurs in December and January.

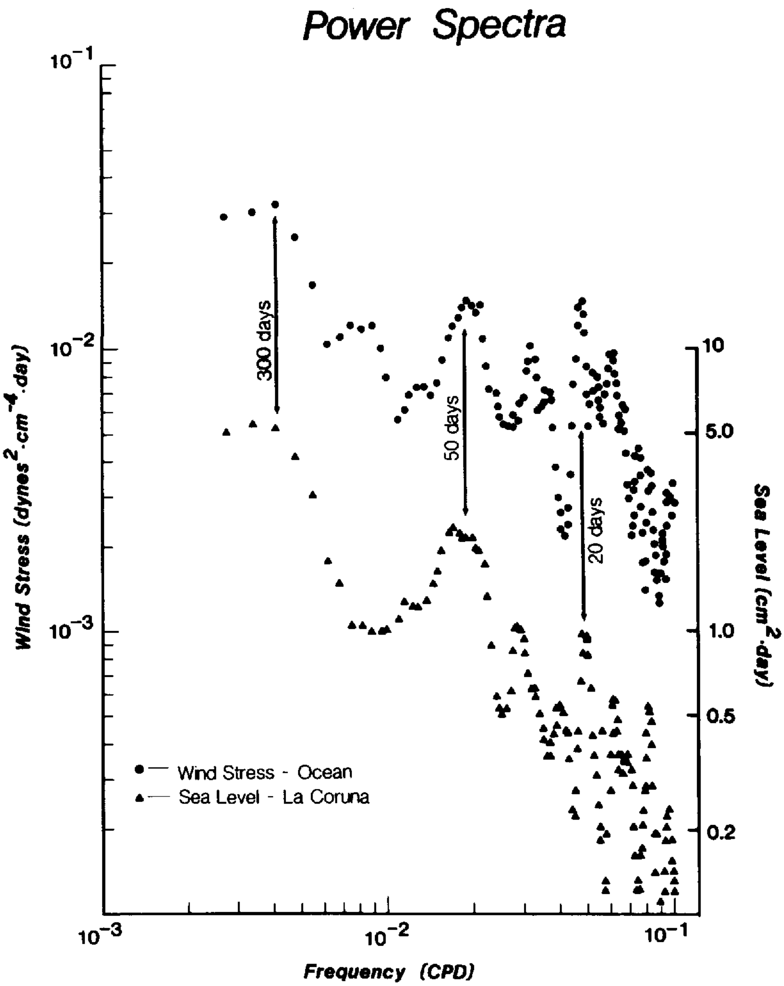
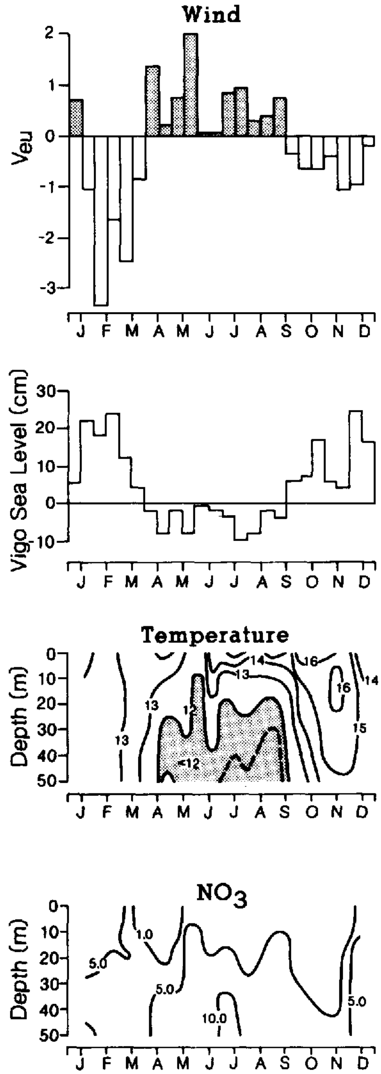


Figure 4. Spectra of northward wind stress 150 km east of Cape Finisterre and sea level (tidal frequencies removed) at La Coruna for years 1977–1980. The length of the three vertical areas represent 90% confidence interval.

The sea level pressure regime responsible for upwelling versus downwelling-favorable winds is dominated by two centers of action (atmospheric pressure cells) in the Atlantic Ocean (Fig. 7). During January, a high pressure cell is located off the northwest coast of Africa. This is actually a continuation of a ridge centered at 50N in eastern Europe and 30–40N in North America. A deep low pressure area is located off the southeast coast of Greenland. The pressure gradient between these two pressure systems forces air to flow onshore off Galicia with a component of stress northward.



Mouth of Ria de Vigo
Data from Fraga and Mourino (1978)

Figure 5. Correlation between upwelling index, sea level, temperature and nitrate at the mouth of Ria de Vigo. Temperature and nitrate data are from Fraga and Mourino (1978).

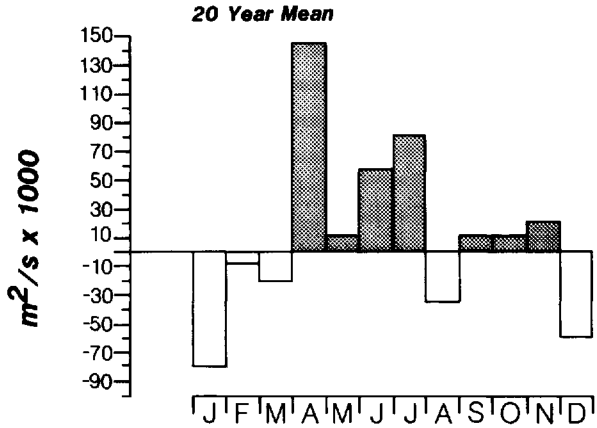


Figure 6. Monthly values of upwelling indices based on 20-year averages of the pressure gradient derived from sea-surface atmospheric pressure (U.S. Navy, 1955). The pressure gradient was derived for a point located 150 km west of Cape Finisterre.

This wind pattern induces downwelling. In July, the high pressure cell (the Azores High) drifts westward and the low pressure cell off Greenland also drifts westward and diminishes in intensity. The resulting pressure gradient forces air to flow southward along the coast of Galicia—a wind pattern that favors upwelling.

There must be considerable year-to-year variability in the two pressure cells that influence winds off Spain. Insofar as upwelling is concerned, a northward shift and strengthening of the Azores High from its mean June or July position would presumably strengthen southward wind stress and, consequently, the upwelling index. During summers when the Azores High is southward of its mean position, upwelling favorable winds would be less frequent than average. Any number of meteorological scenarios involving the strength and position of the Azores High and the northern Atlantic Low off Greenland or Labrador would produce variations in the strength of upwelling favorable winds. A working hypothesis is that monthly upwelling indices vary from year to year, thus affecting the amount of nitrate present at the mouths of the rias. For example, the upwelling indices for years 1977 and 1980 differed greatly (Blanton *et al.*, 1984: see their Fig. 2). The upwelling index in summer 1977 was relatively strong and constant while that in summer 1980 was weak and variable.

We have calculated monthly mean and 6-month mean upwelling indices based on 4 estimates of the sea-surface pressure field each day. The errors associated with the mean values are discussed in the Appendix. Errors when comparing individual months are estimated to be 0.5–1.0 $m^2 s^{-1}$. One should cautiously compare values of the upwelling index within a year and between adjacent years in the 6-month means. The trends and extreme values discussed below remain significant within the expected errors.

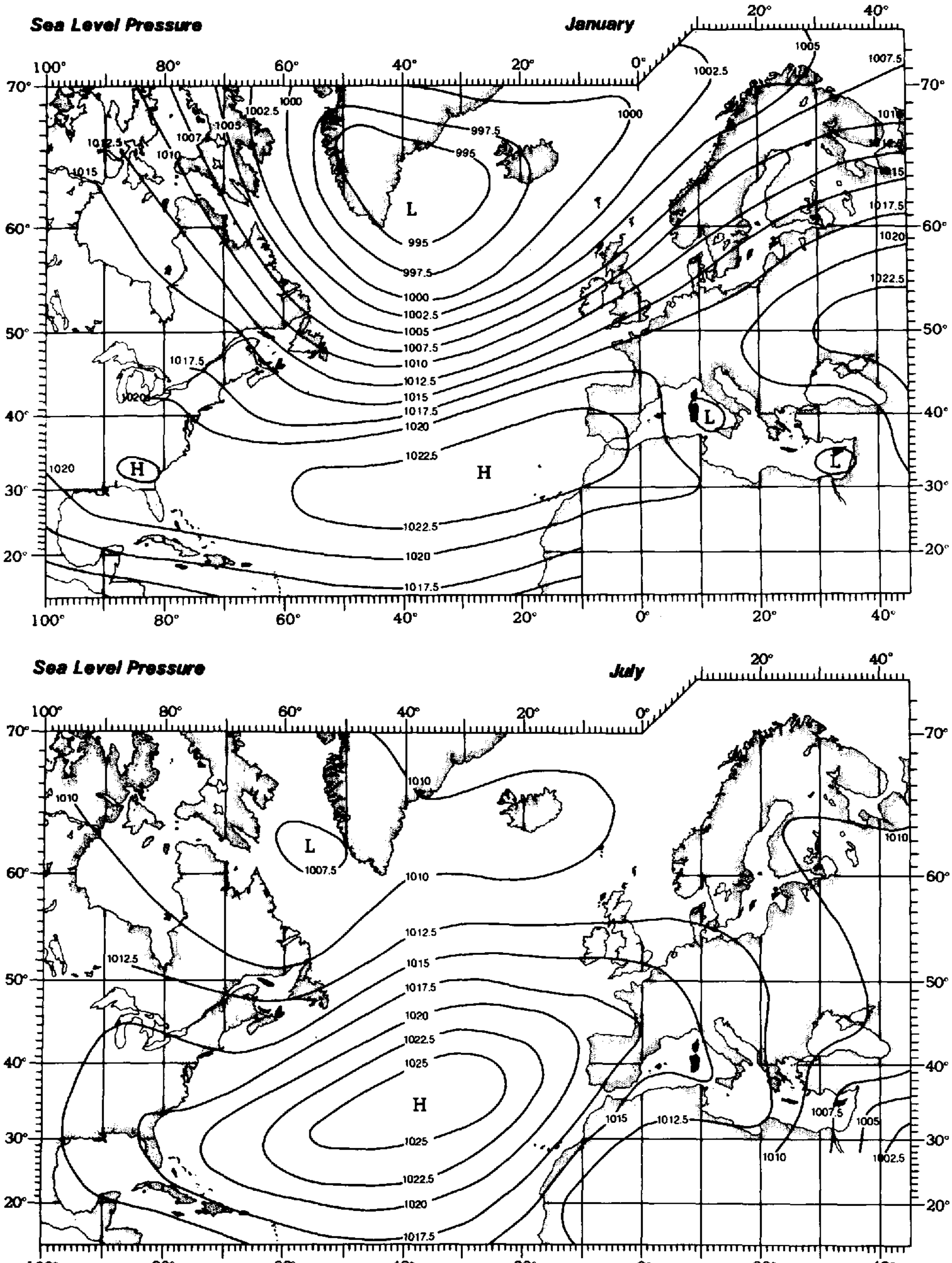


Figure 7. January versus July sea level pressure patterns (from U.S. Navy, 1955).

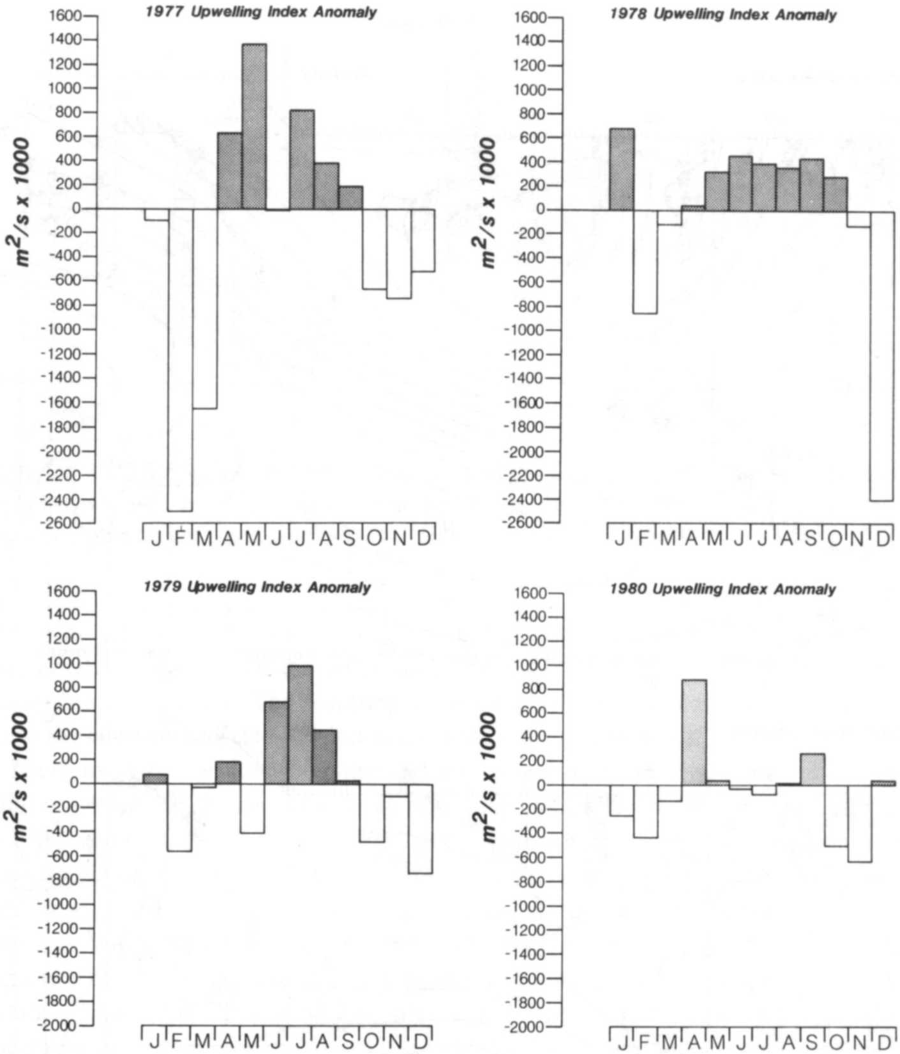


Figure 8. Seven consecutive yearly graphs of the monthly upwelling indices from 1977 through 1983.

Using 0.25-day values for the upwelling indices over an 11-year period from 1973 through 1983, we have averaged these data by month and subtracted the monthly values for the 20-year mean. We clearly see examples of interannual variability (Fig. 8). In some years, a clear change to a positive upwelling index began in April and ended after September (see years 1977, 1979, 1981). During the period in 1980, the index was weak and variable except during April. During 1983, the upwelling index

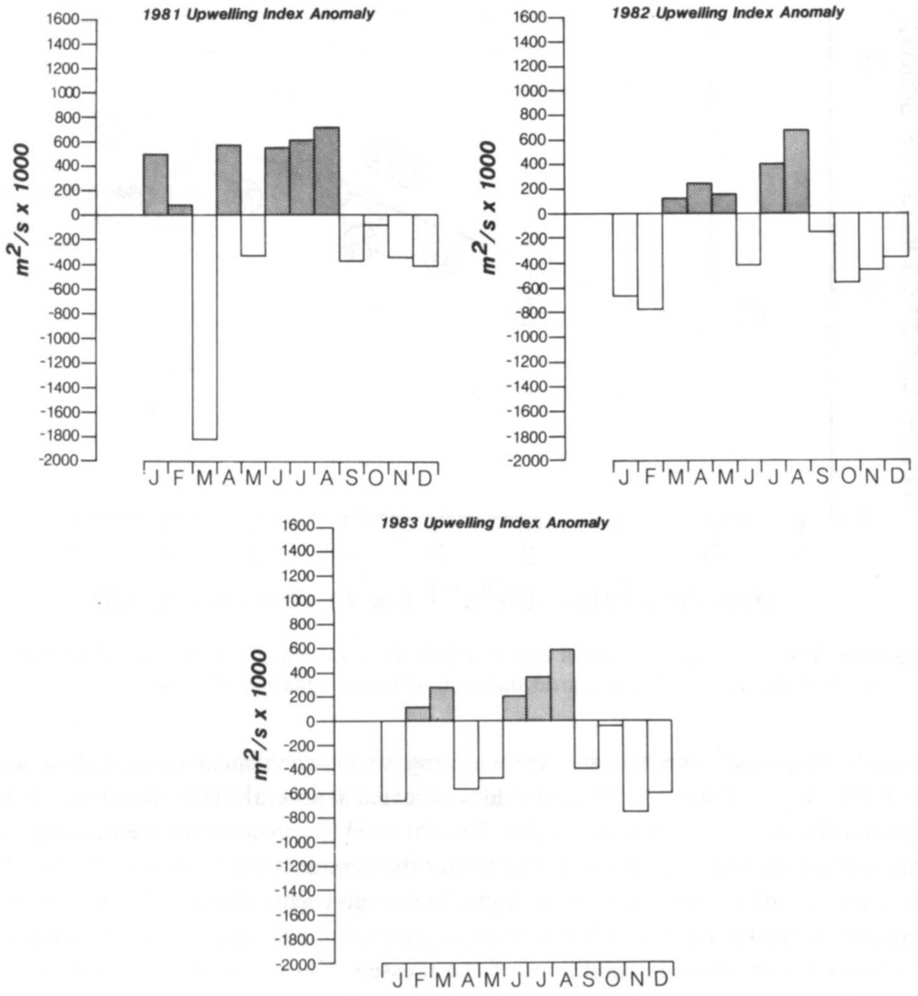


Figure 8. (Continued)

was negative (or not significantly different from zero) during April and May and only three months were upwelling favorable during the "typical" season.

We hypothesize that upwelling indices are related to the condition of mussels produced in the rias. We have extracted a 6-month sequence, over the months April through September, of upwelling indices for each year of a 17-year period. We define this period as the upwelling season (Blanton *et al.*, 1984). We averaged these six values from each year. These averages define the average volume flux of water advected offshore by the winds and replaced by nitrate-rich water from below. These values were correlated with a mussel condition index based on the meat content (percent solid) of

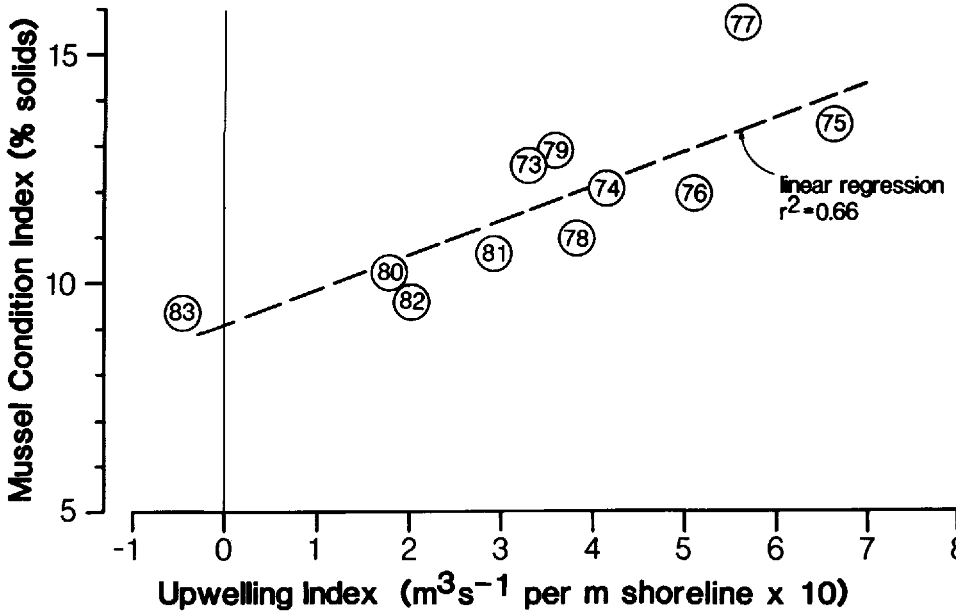


Figure 9. The relationship of mussel condition (MCI) to upwelling (UI) over an 11-year period from 1973 through 1983. The regression line (---) has an equation: MCI = 9.1 + 7.7 UI.

mussels harvested from Ria de Arosa during years when meat content data were available (Fig. 9, Table 1). We used values collected at several sites in the Arosa by the Spanish Department of Public Health. Percent solid is a measure of the meat quality commonly used to grade shellfish. The higher the percent solid value, the "better" the meat quality of the mussel (for example, higher glycogen content). This index is a function of temperature which can change seasonally, but year-to-year variations in the index reflect growing conditions of the mussels. Thus, the percent solid value is high when nutrients associated with upwelling produce favorable growth conditions. We assume that a given season of upwelling affects the mussel harvest in the same year because peak harvests occur during autumn after the upwelling season ends. Thus, we would predict that the condition of mussels would be good in 1975 and 1977 because upwelling in these years transported relatively large amounts of nitrate into the estuaries.

The upwelling fluxes diminished from a high of 0.57 m^2/s in 1977 to a minimum of -0.047 m^2/s in 1983. This trend (Fig. 9, Table 1) suggests that inputs of inorganic nitrogen from the ocean have decreased during this seven year period, a result well within the expected error of the means (see Appendix). The 1983 flux suggests average downwelling conditions over a period when there is usually upwelling. The condition of mussels in 1982 and 1983 was particularly poor when meat content was about 9%. Meat content was almost double for the 1977 upwelling season.

Table 1. Summary of upwelling fluxes during April through September of years 1969 through 1983. The upwelling index may be interpreted in units of m^3s^{-1} per meter of shoreline.

Year	Upwelling index ($m^2s^{-1} \times 1000$)	Mussel conditions index (% solid)
1969	+438	
1970	+389	
1971	+339	
1972	+636	
1973	+327	12.6
1974	+414	12.1
1975	+665	13.5
1976	+502	12.0
1977	+565	15.8
1978	+378	11.1
1979	+360	12.9
1980	+180	10.2
1981	+290	10.7
1982	+200	9.7
1983	−47	9.5
1984	+502	
1985	+154	

4. Conclusion

Upwelling indices (Table 1) have been derived from the pressure gradient at a point located 150 km off Cape Finisterre. This gradient is probably related to two atmospheric pressure centers of action: (1) the Azores High and (2) the Labrador or Icelandic Low (Fig. 7). Interannual variations in the strength and position of these two pressure cells are likely to have a measurable impact on the strength of upwelling that occurs off the coast of Spain and on the condition of mussels utilizing the nitrogen provided by upwelling.

Two years provided a test of this hypothesis: 1977, a year of relatively intense coastal upwelling and 1983, a year of net downwelling during what is normally an upwelling season. These extreme conditions support our hypothesis. The mussel condition index was lowest (9.5%) during 1983 and highest (15.8%) during 1977.

Long range forecasts of synoptic scale weather patterns could be used to predict the potential nutritional value of mussels harvested in the rias in Spain and allow aquaculture practices to minimize economic damage. Such forecasts are presently being developed. Their development is likely to accelerate as interest intensifies to improve the accuracy of long range (seasonal and annual) forecasts.

Earlier work with a mussel growth simulation model (Wiegert and Pensa-Lado, 1982) predicted the carrying capacity (the standing biomass of mussels in the Ria) for optimum mussel production in the Ria de Arosa under average upwelling conditions. When upwelling is low, the high mussel population density results in lower biomass of individual mussel and thus poor marketability. The carrying capacity is determined by the number of rafts, the number of hanging ropes on each raft, and the density of mussels per unit of rope. The new ropes containing small seed mussels are prepared by the fisherman in early spring before the onset of the upwelling season. If the fisherman had advanced knowledge that upwelling during the subsequent summer growing period was likely to be poor, they could deploy fewer mussels per unit rope or fewer ropes on the rafts. Overall production (total tons produced per raft) would be lower during a growing season with low upwelling, but the meat quality of these mussels would be satisfactory for market sale.

Acknowledgments. We wish to thank Mike Hagin, Terry Herring and Barbara Blanton who helped process much of the data presented in this paper. Drafting and technical typing were done by Suzanne McIntosh, Anna Boyette and Susan Salyer. We appreciate the helpful comments of David Menzel on earlier drafts of this paper.

We appreciate the efforts of the Instituto Nacional de Meteorologia in Madrid and the Instituto Nacional de Meteorologia, Centro Zonal de Malaga for providing us the sea surface pressure fields used in computing the upwelling indices. This work was sponsored by a cooperative agreement between the Governments of Spain and the United States.

APPENDIX

The errors associated with the calculation of upwelling indices are caused by uncertainties in the pressure field values over a known distance scale. These values were picked off pressure maps with a resulting resolution of 0.1 m^2s^{-1} in individual estimates of volume transport, V_e. Four pressure maps per day were analyzed to compute the monthly mean values of V_e (Fig. 8) and the 6-month means (Table 1). These samples are not independent because there are natural periodicities in the wind stress spectrum (Fig. 4).

To estimate the expected error in the means we used the one-term asymptotic approximation (Flierl and McWilliams, 1977) which assumes that the wind spectra is essentially red. Thus, the expected error (E) is

$$E = (2\sigma^2 t_I / T)^{1/2}$$

where σ^2 = variance of V_e, T is the sampling period, and t_I is the integral time scale for wind stress fluctuations and is assumed to be $t_I = 5$ days which is representative of the

Table A1. Expected error, $E(m^2s^{-1})$ for $t_I = 5$ days for maximum and minimum monthly variances observed in 1982.

T(days)	$\sigma^2(m^4s^{-2})$	$E(m^2s^{-1})$
30	0.7	0.48
30	3.0	1.0
180	0.7	0.20
180	3.0	0.41

time scale of the passage of weather systems. We estimated E for the 1982 upwelling season for $T = 30$ days and $T = 180$ days. Variances ranged from $\sigma^2 = 0.7\ m^4s^{-2}$ (July) to $\sigma^2 = 3\ m^4s^{-2}$ (April) (Table A1).

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Received: *7 October, 1986;* revised: *31 March, 1987.*